SIGNAL DELAY MEASUREMENT METHOD FOR TIMING SYSTEMS

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Abstract

In this paper, a method for measuring the absolute signal delays of active optical transmission lines will be presented. This measurement method is an essential part of the timing system for FAIR (Facility for Antiproton and Ion Research).

To prevent interference of the timing signals whose delays are to be measured with the measurement signal sequence, the latter is transmitted on a separate optical carrier in the same fibre. By using a wavelength selective mirror at the end of the transmission line, the optical measurement signals are reflected and led back to the measurement unit. The measurement sequence consists of a number of sinusoidal signals with different frequencies that are modulated one by one on the optical carrier. For each frequency a phase comparison of the outgoing and returning signal is performed. In the last step, the absolute delay is calculated from the obtained phase values by using an algorithm.

It will be shown that this method enables cost efficient delay measurements with an accuracy of better than 100 fs.

INTRODUCTION

Different methods are used to provide phase stable reference signals e.g. for cavity synchronisation. All methods deliver one or more reference signals [1-12], mostly sinusoidal clock signals, to several points of the facility. To transmit the reference signal, standard single mode fibres (SMFs) are used. The transmission process should add as little as possible disturbances, like noise and variation of the signal delay, to the reference signals. Noise leads to fast phase fluctuations (jitter) and the variation of the signal delay causes slow phase shifts (drift) [13]. Many timing systems measure the delay changes and compensate them with phase shifter or delay devices, either optical [6-9] or electrical [10-12]. A common basic principle [6-12] is sketched in Fig. 1. For observation of the delay changes, a phase comparison of the outgoing and returning signal is performed.

A disadvantage of this functional principle is the high attenuation (about 15 dB [6], page 14), having effect on both the part of the signal that reaches the receiver (*Rx*) and the part of the signal that is reflected. Caused by the high attenuation, the signal power fed to the receivers is lower than in an optimal case [1], page 5. This results in a lower signal-to-noise ratio (SNR) and thus in more phase jitter. On the one hand, this affects the phase stability of the transmitted reference signal, on the other hand the phase comparison is less precise. The latter leads to disturbances while compensating the delay change in the fibre. These disturbances cause delay correction errors and therefore additional phase instabilities.

A further disadvantage is the fact that the signal for detection of the delay changes and the reference signal have the same frequency. Since the accuracy of the phase measurement, by approximation, is not depending on the frequency used, an accurate reading of the delay changes is more easily achieved with a higher frequency than with a lower one. Normally the frequencies of the reference signals are specified by other boundary conditions. Therefore within the basic principle of Fig. 1 it is not possible to increase the frequency to get a better delay observation.

DWDM

Relatively low frequencies (between 100 kHz and 200 MHz) are used in the FAIR timing system. Therefore the idea arose to determine the delay by other means. Using the *dense wavelength division multiplex* (DWDM) method, it is possible to transmit both signals on different optical carriers of different wavelengths over a shared fibre. In this way the two clock signals and the measurement signal can be sent independently of one another (Fig. 2).

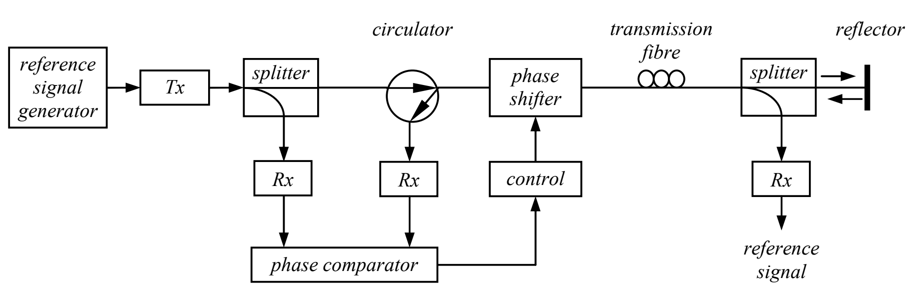

Figure 1: Basic principle of a frequently used timing system. High attenuation, reference signal = measurement signal.

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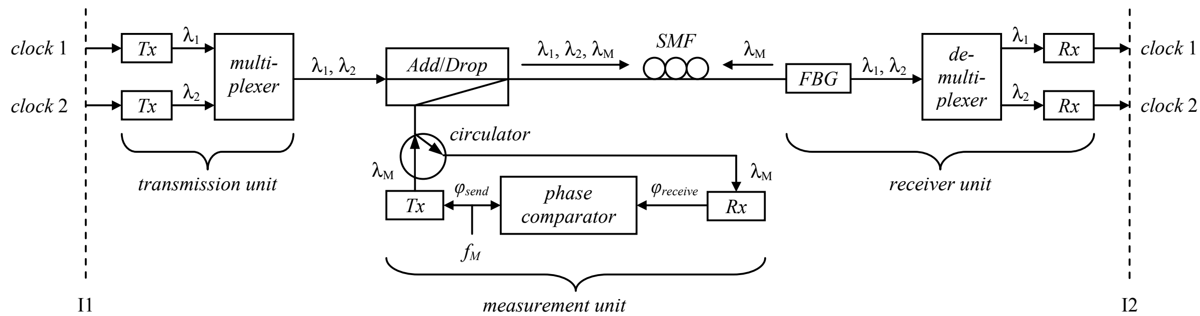

Figure 2: A single optical transmission branch of the FAIR timing system with DWDM: Two transmission channels and one separate measurement channel. Low attenuation, reference signal ≠ measurement signal.

The two clocks are optically multiplexed, i.e. they are modulated to two different optical wavelengths λ_1 and λ_2 in the transmitters (*Tx*) and combined into a single fibre in a multiplexer (Fig. 2). The two optical signals then pass through an add/drop multiplexer, the transmission line (SMF ≤ 1 km) and an FBG (fibre Bragg grating). In the demultiplexer, the wavelengths are separated again and fed to two separate receivers (*Rx*).

The delay changes on the transmission fibre are compensated in a next step in two other components called the Reference Generators [1-4]. Therefore the Reference Generators need information about the absolute clock signal delay. This is determined by the measurement unit and provided to the Reference Generators. The measurement signal for determining the delay is modulated to a third optical carrier λ_M. Via a circulator, the measurement signal is delivered to the add/drop multiplexer which combines the signals λ_1, λ_2 and λ_M. After passing through the SMF, all signals meet the FBG, which represents a wavelength-selective reflector that exclusively reflects λ_M while letting through the other two signals. The measurement signal now returns, is decoupled in the add/drop multiplexer and fed to the measurement receiver via the circulator.

In contrast to the conventional method in Fig. 1, the attenuation between the transmitter and the receiver in both the measurement channel and the transmission channel is less than 4 dB, instead of 15 dB.

MEASUREMENT METHOD

After creation of the basic conditions in Fig. 2, the following measurement method can be applied.

Step 1

In step 1, a sinusoidal oscillation with the frequency $f_{M,1}$ is modulated in the transmitter (*Tx*) to the optical wavelength λ_M (Fig. 2). After the signal had passed through the transmission fibre, it is reflected, runs back and is fed to the receiver of the measurement unit. In the receiver, the optical signal is converted to in an electrical signal and delivered to the phase comparator. A phase comparison of the outgoing and returning signal is performed. The delay is determined in step 1 with the measured phase difference $\Delta\varphi_{M,1}$ (Fig. 3) and the first value can be calculated

$$\tau_{M,1} = \frac{\Delta\varphi_{M,1}}{2\cdot 360°}\cdot T_{M,1}\,. \tag{1}$$

It is mandatory that the period of the sinusoidal oscillation $T_{M,1}$ shows the following relation to the true value of delay τ

$$\frac{1}{f_{M,1}} = T_{M,1} > 2\tau \tag{2}$$

to achieve an unambiguous result. This first determination of the delay $\tau_{M,1}$ is relatively inaccurate. The accuracy of the delay determination depends on the period of the measurement frequency and on the precision of the phase comparator $\Delta\varphi_{accu,step}$. The following equation is valid for all 1 to N steps

$$\tau_{accu,step} = \frac{\Delta\varphi_{accu,step}}{2\cdot 360°}\cdot T_{M,step}\,. \tag{3}$$

Step 2 to N

To improve the accuracy of the first delay determination, in step 2 a measurement signal 10 to 100 times higher in frequency is used and a second phase comparison is performed. Now the frequency is so high that inequality (2) is not fulfilled anymore. As a consequence, the delay determination becomes ambiguous (Fig. 4)

$$\tau_{M,step} = \underbrace{\frac{K_{step}}{2}}_{\text{indeter-minate}}\cdot T_{M,step} + \frac{\Delta\varphi_{M,step}}{2\cdot 360°}\cdot T_{M,step}\,, \tag{4}$$

if the integer factor K_2 is not known. But this factor can be determined by using $\tau_{M,1}$ from the first delay determination

$$K_{step} = \left\lfloor \frac{2\tau_{M,step-1}}{T_{M,step}} \right\rfloor, \tag{5}$$

so an unambiguousness result is achieved again. Since K_{step} is rounded down, the phase difference $\Delta\varphi_{M,step}$ must

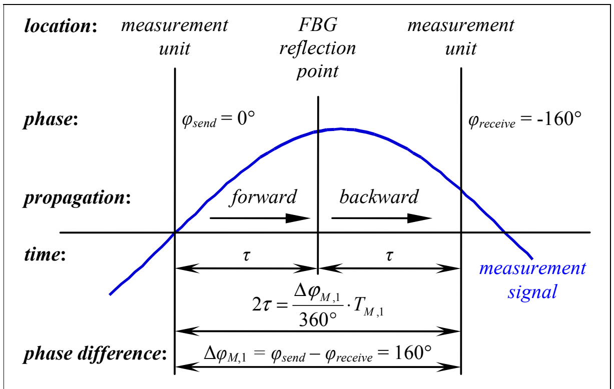

Figure 3: Signal delay measurement – Step 1.

be positive and this is always true when using the following definition[†] (see Fig. 2)

$$\Delta\varphi_{M,step} = (\varphi_{send} - \varphi_{receive}) \bmod 360° . \tag{6}$$

To prevent an incorrect determination of the factor K_{step} with Eq. (5), note that the error of the first measurement $\tau_{accu,1}$ needs to be significantly smaller than the period of the second measurement frequency. This is also valid for all further phase measurements

$$\tau_{accu,step-1} << T_{M,step} \tag{7}$$

In step 3, the next phase measurement with a still higher frequency is performed and the delay is determined again with Eq. (4) and (5). Thus, the accuracy is further improved according to Eq. (3). By approximation, it can be assumed that the phase measurement accuracy is independent of the frequency

$$\Delta\varphi_{accu,1} = \Delta\varphi_{accu,2} = \ldots = \Delta\varphi_{accu,N} = \Delta\varphi_{accu} \tag{8}$$

and therefore the accuracy of the delay determination is rising with the measurement frequency.

MEASUREMENT ACCURACY

In order to identify how precise the absolute delay can be measured, at first additive noise due to transmission will be considered and which effect it had on the accuracy. Afterwards the need of a permanent calibration of the measurement unit and finally the effect of the time base will be described.

Signal Quality

To generate the measurement signal and carry out the phase comparison, a network analyser is used. The network analyser passes the measurement signal to the transmitter and is fed with the returning signal via the receiver to perform the phase comparison (Fig. 2).

† Modulo definition : $a \bmod b := a - \left\lfloor \frac{a}{m} \right\rfloor m$

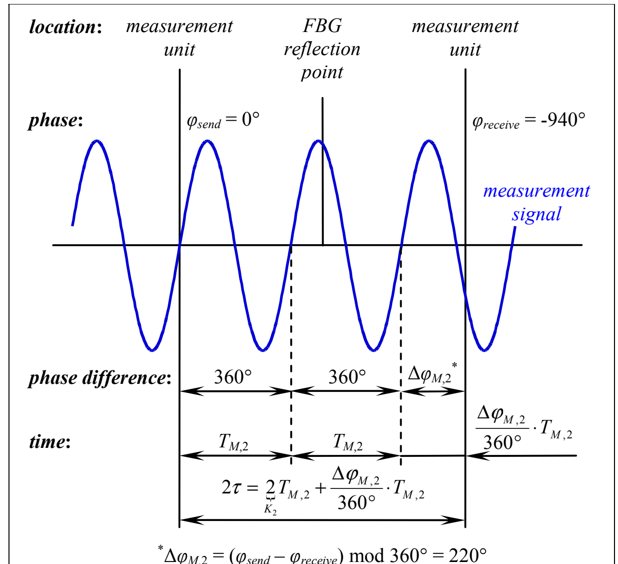

Figure 4: Signal delay measurement – Step 2.

The use of sinusoidal measurement signals pays off now. Thus the measurement bandwidth can be reduced to 10 Hz and this is how a large SNR of ≥ 90.6 dB[‡] has been achieved in the prototype of the FAIR timing system [1], page 7. As a consequence, the phase jitter of the measurement signal is ≤ 0.0012° and therefore negligible compared with the measurement accuracy of the network analyser. The quality of the measurement signal transmission is so good that the accuracy of the measured phase difference $\Delta\varphi_{accu}$ only depends on the phase comparator in the measurement unit which is specified as < 0.4° in the prototype.

Principle of Permanent Calibration

The specification of measurement accuracy of < 0.4° is only valid within a short time frame after calibration[§]. So it is not sufficient to calibrate the measurement unit only once before operation, because a sustained continuous operation over months must be possible without decrease of the measurement accuracy. For that reason, a calibration routine for the operating system has been developed. Fig. 5 shows how in the FAIR timing system the measurement unit can be connected with all transmission branches and a mirror via an optical switch. This configuration enables a sequential measurement of all branches with only one measurement unit. Thus the costs are reduced significantly. Once per measurement cycle, for all frequencies the phase differences that occur upon reflection on the special mirror are measured. The mirror is placed nearby the optical switch (< 1 m) for calibration. Thus the measurement unit is fed with calibration data for correction of the measured phase differences during delay determination.

‡ For fibre lengths of L > 1 km, the dominant Rayleigh noise increases slightly (SNR ≥ 80 dB) [1], page 6.

§ The output value of the phase comparator depends e.g. on the temperature [6], page 46.

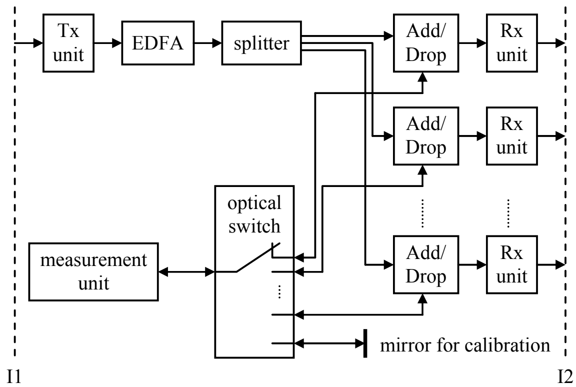

Figure 5: Permanent Calibration.

Not only the phase comparator, but the complete measurement unit is calibrated. This is in particular necessary because of the anticipated delay drifts of the optical transmitter and receiver caused by temperature changes [6, 10] as well as their generally not linear phase responses. From literature, no calibration method of this kind is known.

Absolute Measurement Accuracy

The absolute accuracy of the delay measurement depends, other than in Eq. (3), not only on the accuracy of the phase measurement $\Delta\varphi_{accu}$, but also on the deviation of the time base $(\Delta T/T)_M$

$$\tau_{accu,abs} = \frac{1}{f_{M,\max}} \frac{\Delta\varphi_{accu}}{2 \cdot 360°} + \underbrace{\frac{L \cdot N_g}{c}}_{\tau} \left(\frac{\Delta T}{T}\right)_M . \tag{9}$$

This means for the prototype, with the following values $f_{M,\max} = 6$ GHz, $\Delta\varphi_{accu} < 0.4°$, the fibre length $L = 1$ km, their group index $N_g = 1.47$, the speed of light $c = 2.9979 \cdot 10^8$ m/s and $(\Delta T/T)_M = 5 \cdot 10^{-9}$ an absolute accuracy of $\tau_{accu,abs} < 117$ fs can be achieved.

Elimination of Time Base Deviation

The real purpose of the delay measurement is to determine the change of the phase at the end of the transmission line, enabling corrections in order to stabilize the overall transmission delay. When this is done without particular precautionary measures, another error occurs, caused by the deviation of the clock signal time base $(\Delta T/T)_{clock}$. The resulting relative accuracy

$$\tau_{accu,rel} = \frac{1}{f_{M,\max}} \frac{\Delta\varphi_{accu}}{2 \cdot 360°} + \frac{L \cdot N_g}{c} \left| \left(\frac{\Delta T}{T}\right)_M - \left(\frac{\Delta T}{T}\right)_{clock} \right| \tag{10}$$

depends on the difference between the time base deviations. Since in the prototype both the measurement and clock signals are derived from the same time base, their time deviations are of the same magnitude

$$\left(\frac{\Delta T}{T}\right)_M = \left(\frac{\Delta T}{T}\right)_{clock} \tag{11}$$

and thus, the second summand in Eq. (10) and therefore the error caused by the deviation of the time bases is cancelled out. As a consequence, the relevant relative delay measurement accuracy depends only on the precision of the phase comparator. Instead of Eq. (10), the following is valid

$$\tau_{accu} = \frac{1}{f_{M,\max}} \frac{\Delta\varphi_{accu}}{2 \cdot 360°} . \tag{12}$$

With the parameters $\Delta\varphi_{accu} < 0.4°$ and $f_{M,\max} = 6$ GHz, the delay measurement accuracy of the prototype amounts to $\tau_{accu} < 92.6\,fs$[**].

Dispersion

Owing to dispersion in the SMF, the delay in the measurement channel deviates from the delay in the transmission channel. With the known dispersion properties of the fibre, the delay deviation can easily be calculated[††] [2], page 113, and the delay in the transmission channels can be determined.

PRACTICAL MEASUREMENT

Now a practical example of the functionality of the measurement method will be presented. The delay in a transmission fibre with $L = 1$ km, $N_g = 1.47$ and $c = 2.9979 \cdot 10^8$ m/s is about

$$\tau = \frac{L \cdot N_g}{c} \approx 4.9 \mu s . \tag{13}$$

According to Eq. (2), in the beginning the first measurement frequency $f_{M,1}$ must be < 100 kHz. Supposing that the accuracy of the phase comparison is $\Delta\varphi_{accu} < 0.4°$ and taking into account the condition in Eq. (7), the measurement frequency can be increased by a factor of << 1800 in each step. For experimental purpose, the 4 measurement frequencies in Tab. 1 have been chosen. After performing these 4 phase comparisons, from the phase differences $\Delta\varphi_{M,step}$ obtained with Eq. (6), the delay for each step is determined according to Eq. (4) and (5). The measurement period per transmission branch amounts to 1 s in the prototype.

Verification

As a first functional test to verify the measurement method, the delay $\tau_{M,4}$ is defined as the true value and the absolute deviation from $\tau_{M,step}$ is calculated. Tab. 1 shows that the measurement accuracy τ_{accu} calculated with Eq. (3) is maintained in each step.

Under to the same assumption that $\tau_{M,4}$ is the true value and using the deviations $|\tau_{M,step} - \tau_{M,4}|$, the phase comparison error $\Delta\varphi_{M,error,step}$ can be calculated. Tab. 1 shows

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[**] This value is valid for the delay of the transmission line up to the FBG (Fig. 2). Delay changes in the receiver unit cannot be observed. Special measures must be taken for stabilisation of the delays in the receiver unit.

[††] The difference between $\lambda_1 = 15551.721$ nm and $\lambda_M = 1548.515$ nm is about 50 ps/km.

Table 1: Practical delay determination – specification of phase measurement accuracy: $\Delta\varphi_{accu} < 0.4°$.

step	$f_{M,\mathrm{step}}$ [MHz]	$\Delta\varphi_{M,step}$ [°]	K_{step} [ ]	$\tau_{M,step}$ [ps]	$\lvert\tau_{M,step}-\tau_{M,4}\rvert$ [ps]	$\tau_{accu,step}$ [ps]	$\Delta\varphi_{M,error,step}$ [°]
1	0.05	175.98	0	4888333.333	277.778	11111.111	0.010
2	0.5	319.73	2	4888133.333	75.000	1111.111	0.027
3	50	289.98	244	4888055.000	2.472	11.111	0.089
4	5000	206.88	24440	4888057.467	:= 0	0.111	:= 0

that the phase comparison error stays below the specified value of $< 0.4°$ in each step as well.

These results led to the assumption that this measurement accuracy will also be achieved at the highest frequency. To examine this, a maximum frequency of $f_{M,\max} = 6$ GHz has been used. Applying Eq. (12) the measurement accuracy is $\tau_{accu} < 92.6$ fs. By means of a test setup specifically developed for this problem, this value has been verified and confirmed [1], page 8.

SUMMARY

A measurement method for determination of the absolute delay in standard single mode fibres with an accuracy of better than 92.6 fs has been presented. This accuracy was verified in practice.

For each measuring, 4 sinusoidal signals are sent sequentially on a separate optical channel through the fibre. The phase difference is measured each time and from the results the delay is calculated. The measurement unit consists of standard components used in telecommunications as well as measurement technology. Essential reasons for the high measurement accuracy are:

a) The low attenuation due to the use of *dense wavelength division multiplex* (DWDM).
b) The principle of permanent calibration.
c) The use of sinusoidal measurement signals, whereby the measurement bandwidth can be reduced to 10 Hz, and the resulting large signal-to-noise ratios of SNR ≥ 90.6 dB.

By means of an optical switch, one single measurement unit is capable of measuring a multitude of transmission fibres. This reduces the overall costs significantly.

OUTLOOK

The accuracy can be improved further by the use of a higher maximum measurement frequency according to Eq. (12). Furthermore, the use of a network analyser prospectively enables the measurement of the transmission attenuation to detect damages on the fibres without additional expenditure.

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